STUDIES FOR STUDENTS.

DEFORMATION OF ROCKS. V.

SUPPLEMENTARY NOTES.[1]

Separation of the outer part of the earth into zones.—In dividing the outer part of the crust of the earth into an upper zone of fracture, a middle zone of combined fracture and plasticity, and a lower zone of plasticity,[2] three factors should be taken into account, (1) the depth of burying, and therefore the vertical pressure, (2) the relative strength and plasticity of the materials, and (3) rapidity of deformation.

If the last two factors were constant, as a result of the first factor the zone of plasticity would be directly below the zone of fracture with a possible narrow transition zone. The greater the strength of materials, and the greater the rapidity of deformation, the deeper is the zone of plasticity. The weaker and more plastic the materials, and the slower the deformation, the nearer the surface is the zone of plasticity. However, as these factors vary greatly there is a wide middle zone of combined fracture and plasticity. Some rocks may be deformed by plastic flow very near the surface, and others by microscopical fracturing at a great depth. As illustrating this, a bed of mud may be deformed without fracture at or near the surface. Upon the other

[1] Figure 101, on page 595, of my paper on the Principles of North American pre-Cambrian Geology, in the Sixteenth Ann. Rept. of the U. S. Geol. Survey, Part I, was taken from Dr. Carl Futterer. The statement, "After Futterer" was in the manuscript list of illustrations, but by mistake this was omitted in printing.

[2] (A) Principles of North American pre-Cambrian Geology, by C. R. VAN HISE; with an appendix on Flow and Fracture of Rocks as related to Structure, by L. M. HOSKINS. Sixteenth Ann. Rep. U. S. Geol. Surv., Part I, 1896, pp. 589–603.

(B) Deformation of Rocks, by C. R. VAN HISE. JOUR. OF GEOL., Vol. IV, 1896, pp. 195–213.

hand the strongest, brittlest rocks in the deepest zone observable may be partly deformed by complex fracturing along intersecting shearing planes, but, however, without spaces between the particles. In the deepest seated zone the fracturing of the mineral particles may be so uniformly distributed as to give slight undulatory extinction only, the ultimate particles between which differential movements have occurred or differential stresses are at work not being discriminated as such even with the most powerful objective. However, in some of the deformed strong rocks even such stress effects as undulatory extinction are not marked, and in this case, the material must have been largely released from strain, just as in the case of viscous liquids which for a time after deformation show stress effects, but which later free themselves from them. Such profound changes are believed to involve recrystallization, water being the agent through which alteration took place.

It is also conceivable that where the deformation is very slow, even strong, brittle rocks may be deformed by plastic flow comparatively near the surface. But as shown by deep tunnels, some of which have in places a superincumbent load of rock a mile thick, if flow does occur, it is very slow indeed. This, too, is in spite of the fact that a tunnel is substantially a cylinder, very long in comparison to its width, and therefore that if the stress amounts to one half of the elastic limit of the rock, flowage would result.[1] But in estimating the stress in the case of tunnels, it is to be considered that the mountain mass does not have vertical but sloping sides, and hence is really a flat cone. While from the above it is clear that the superincumbent weight of thousands of feet of rock is not sufficient to cause flowage in very strong rocks, it is equally certain that in softer rocks, such as shale and coal, flowage occurs under much less weight than this, as shown by the creeping and closing of some galleries in mines, which at a depth of one thousand feet or less, have from time to time to be cut out, so as to compensate for the creeping flow which has tended to close them.

[1] Loc. cit., (A), pp. 592; (B), p. 199.

Notwithstanding all of the foregoing difficulties and qualifications, it is still possible in the field to place most masses of rock somewhat definitely in one of the three zones, the predominant phenomena in most cases of tolerably homogenous rocks being either fracture or flowage, while in heterogeneous rocks of many districts fracture and flowage are both of importance.

Plastic flow produces folding.—It has been pointed out that the zone of plastic flow is in the zone of folding.[1] Under the conditions of flowage, where the laws of hydrodynamics obtain, there is a constant tendency to approach equilibrium. But because rocks are heterogeneous both in strength and magnitude of elements, this tendency results in very complex flowage, and the resultant forms of deformation include all varieties of rock folds. However, this complexity of flow presents no exceptions to the laws of hydrodynamics.[2] At any moment, for any homogeneous small plastic area, for any forces which may be at work, the deformation obeys the laws of hydrodynamics, *i. e.*, the material moves in the direction of least stress.

Complex folds.—It has been stated that the two sets of simple folds making up complex folds have a tendency to be at right angles to each other. This appears to follow as a necessity from the laws of mechanics.[3] Any number of pressures in all directions may be analyzed into three pressures at right angles to one another, these being maximum, mean, and minimum pressures. At the outset of the action of the folding forces, because the beds and formations act as transmitters of forces, there will be a tendency for two of the principal directions of stress to be parallel to the bedding, and the other of the principal directions of stress to be normal to the bedding. Even after the layers are inclined it will still be true that at any moment the tangential forces may thus be analyzed. Thus we have the explanation of rectangular systems of folds in districts of complex folding. The closer folds are at right angles to the greater horizontal pressure, and the more open cross folds are at right

[1] Loc. cit., (A), p. 594; (B), p. 202.

[2] In my previous articles on deformation by plastic flow I have used the word *hydrostatic*. The word *hydrodynamic* should have been used.

[3] Loc. cit., p. 627 (A); (B) p. 345.

angles to the less horizontal pressure. It may be that the tangential forces in either direction constitute a vertical couple, and in such cases monoclinal folds may be produced.[1]

While for a given district it may be assumed for definite areas that the average direction of the maximum and mean forces remain the same for considerable intervals of time, it does not follow that in the adjacent districts, or in another part of the same district, the relative values of these may not be reversed, and thus the direction of the closer folds for one part of the dis-district be that of more open folds of another part of the district.

Moreover, as a result of the action of the formations as transmitters of forces, plications may be formed intermediate between the two prevalent directions. Minor plications deviating from the general directions of folding are particularly likely to be seen when the two tangential forces are about equal, thus forming domes, and at places where a strong formation plunges below the surface as a result of the cross folding. In such cases the strata, especially the weaker strata, may be in a set of radial minor plications, mantling around the dome or mantling around the plunging mass of strong material. At each point the axes of the minor plications represent the dip of the slopes of the dome or of the stronger bed. Such plications result from the necessary readjustment between the beds. To illustrate—when a piece of leather is placed upon a hemisphere, it will fit closely at the top, but cannot be made to fit along the sides of the hemisphere unless portions be cut out. In nature the rocks cannot be cut out, and as a consequence we have the radial flutings, which in the case of anticlines plunge away from the crest, and in the case of synclines plunge toward the trough. These flutings, and the consequent radiating or converging character of the minor axial planes, are frequently of great assistance in determining whether a given mountain mass is an anticlinorium or a synclinorium. However, it appears that the arrangement of these flutings is no exception to the general law, for there is always a marked tendency for strong beds to decompose the

[1] Loc. cit., (A), pp. 626–627; (B), pp. 343–345.

forces into components parallel to their strike and dip at any given point, and thus the axes of these minor plications would correspond to the local directions of greater and less thrust.

Monoclinal anticlines and synclines.— In regions of close monoclinal folds, the axial planes of which have a low dip, and especially if there be a little fanning, it may be difficult to discriminate between anticlines and synclines. This principle is well illustrated by the relations of the limestone and schist in the Housatonic

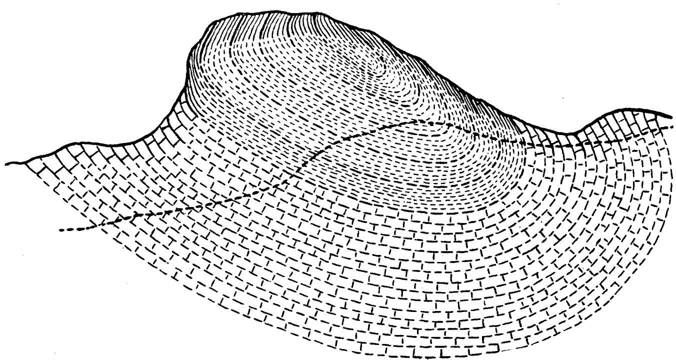

FIG. 1.

Valley. The Stockbridge limestone composes the lowlands for the most part. Rising from the lowlands are numerous schist ridges, varying from small hills to mountains such as Tom Ball and Lenox, the summits of which are from several hundred to a thousand or more feet above the valley. These schist ridges are, in fact, synclines which rest upon the limestone. However, observations of the dip across the ridge would in many cases lead to the conclusion that they are anticlines, as upon opposite sides of the ridge there is a divergence downward in the dip (Fig. 1). Of course dip of bedding is here meant,— not dip of schistosity, which, while variable, dips with considerable regularity to the east. This anticlinal appearance is well illustrated by the hill called Turnip Rock and the larger hill known as Barack M'Teth, and also by Tom Ball, all in, or partly in, the area covered by the Sheffield topographic sheet of Massachusetts. In each of

these cases, if the dips of the schist observed in crossing a ridge were alone considered, the ridges would unquestionably be called anticlines. Also if the layers of limestone immediately adjacent to the schists were taken into account, the same con-

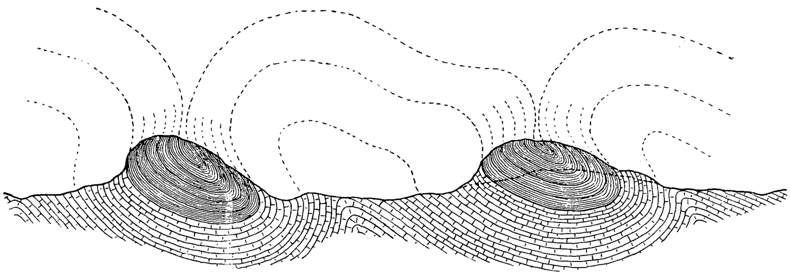

FIG. 2.

clusion would be reached (Fig. 2). While the dips in each case, both on the east and west sides of the ridges, are generally to the east (locally west dips are formed on the west sides of the ridges), on the east side of each ridge the dip is flatter than on the west side, thus making a divergence downward. Fortunately, however, in the case of Turnip Rock, the limestone at both the north and south ends of the hill is traced to the schist, and is found to plunge under it. In fact, at the south end of the mountain the limestone can be almost continuously traced under the schist, and seen to bend suddenly from an almost flat position to its overturned position. A study of Barack M'Teth and other mountains and their relations shows that Turnip Rock is unquestionably a type of the remainder of the ridges of the district. They are nearly recumbent, slightly fan-shaped synclines. In the areas between the schist ridges the limestone has for the greater part of the distances a continuous rather moderate dip to the east. It is only near the east side of the ridges that the sudden turning over of the anticline may be found. A section through two synclinal schist ridges, with intervening limestone, is generalized in Fig. 2. It is to be noted that if the plain of denudation had cut somewhat lower, so as to remove

all but remnants of the schist (see dotted, lines Figs. 1 and 2), these lower parts would appear as ordinary synclines, with little or no evidence of fanning. Indeed, in the case of a number of the schist ridges in the Housatonic Valley, erosion has so far advanced as to have left only the lower part of the synclines. Thus one who studies two adjacent schist ridges cut to different depths and overlooks the intermediate anticline of limestone, which is difficult to discover because of the poor exposures, might infer that one is an anticline and therefore is overlain by the limestone, and that the other is a syncline and is therefore underlain by the limestone. (See Fig. 2.) The conclusion would thus be reached that there are two schist formations, one of which is older than, and the other of which is younger than, the limestone, whereas there is only a single schist formation, and all ridges whether apparently anticlines or synclines, are parts of synclines of the same type and all overlie the limestone.

Positions of cleavage in anticlines and synclines.—In another place I have given the general law:[1] "On opposite limbs of a fold the cleavage usually dips in opposite directions. Upon opposite sides of an anticline the cleavage usually diverges downward, and on opposite sides of a syncline it usually converges downward." No instance of this principle was given. Since this was written it has been found that this principle is well illustrated on Mount Barack M'Teth above mentioned, upon the southern part of Mount Washington in Massachusetts, and upon all of the various synclines of Manhattan schist of Manhattan Island and of the area to the northward. In each of these cases the areas are synclinal, and in all of them the cleavage on opposite sides of the ridges converges downward. Subordinate anticlines of the Manhattan schist, in synclinoria which illustrate the above principle, show the reverse principle, that is, the cleavage diverges downward upon opposite sides of the minor anticlines. This principle is also illustrated at the anticline of Fordham gneiss a short distance south of Harlem Bridge. In many of these cases the folds are monoclinal, and

[1] Loc. cit., (A), pp. 649–650; (B), p. 474.

in some of them the cleavage is also monoclinal, but still shows divergence or convergence downward upon opposite sides of a fold according to the law. In the monoclinal syncline the monoclinal cleavage on opposite sides of the limb converges downward, and in the monoclinal anticline the monoclinal cleavage on opposite sides of the limbs diverges downward.

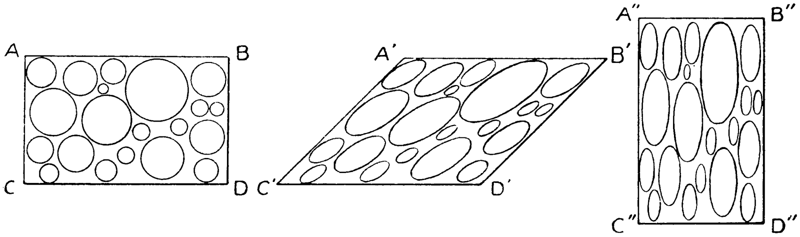

FIG. 3.

It may be suggested that in cases where metamorphism has gone so far that it is difficult to determine bedding this principle of the convergence downward of cleavage on opposite sides of a syncline, and divergence downward of cleavage on opposite sides of an anticline, may be used to determine whether a series of folded exposures are anticlinal or synclinal. In another case, where the bedding is somewhat obscure and dips difficult to get, it may be used as confirmatory evidence of the observations made upon the bedding.

Relations of cleavage produced by shearing to shortening.— In the production of cleavage as a result of simple shearing, Professor Hoskins has pointed out that the cleavage approaches parallelism to bedding faster than does a line originally normal to the bedding.[1] As the actual positions of the cleavage resulting from definite shears and the relations of original circles to equivalent flattened ellipses (Fig. 3) are matters of some practical importance in the field, Mr. E. C. Bebb was asked to tabulate the positions of the major axes of the flattened ellipses, the values of

[1] Flow and Fracture of Rocks as Related to Structure, by L. M. HOSKINS. Appendix to Principles of North American pre-Cambrian Geology, by C. R. VAN HISE, Sixteenth Ann. Rept. U. S. Geol. Surv., Part I, 1896, pp. 870–871.

the major and minor axes of the ellipses compared with those of the diameters of equivalent circles, the ratios between the last two, and the ratio between the diameters of the original circles and the minor axes of the equivalent ellipses, for rotations of a vertical line at intervals of 5°.[1] This table is as follows, the positions of the major axes of the ellipses being calculated to the nearest 1′:

1 Deviation of a vertical line from the perpendicular, as a result of simple shearing	2 Angle between major axes of ellipses and the vertical, resulting from shearing circles	3 Complements of the angles given in (2) or the dip of the cleavage	4 Length of minor axes of ellipses compared with diameters of original circles	5 Length of major axes of ellipses compared with diameters of original circles	6 Ratios between minor and major axes of ellipses	7 Ratios between minor axes of ellipses and diameters of original circles
5°	46° 15′	43° 45′	.957	1.045	1 : 1.091	.957 : 1
10	47 31	42 29	.916	1.092	1 : 1.193	.916 : 1
15	48 49	41 11	.875	1.143	1 : 1.306	.875 : 1
20	50 10	39 50	.834	1.198	1 : 1.436	.834 : 1
25	51 34	38 26	.794	1.260	1 : 1.587	.794 : 1
30	53 3	36 57	.752	1.329	1 : 1.768	.752 : 1
35	54 39	35 21	.709	1.410	1 : 1.987	.709 : 1
40	56 23	33 37	.665	1.504	1 : 2.262	.665 : 1
45	58 17	31 43	.618	1.618	1 : 2.618	.618 : 1
50	60 24	29 36	.568	1.759	1 : 3.096	.568 : 1
55	62 46	27 14	.515	1.943	1 : 3.775	.515 : 1
60	65 27	24 33	.457	2.188	1 : 4.787	.457 : 1
65	68 30	21 30	.394	2.538	1 : 6.446	.394 : 1
70	71 58	18 2	.325	3.073	1 : 9.446	.325 : 1
75	75 55	14 5	.251	3.983	1 : 15.868	.251 : 1
80	80 17	9 43	.170	5.842	1 : 34.30	.170 : 1
85	85 2	4 58	.0866	11.517	1 : 134.9	.0866 : 1

The facts of this table are graphically represented by Fig. 3 for a rotation of a vertical line amounting to 45°.

It is of interest to note that the table shows that with the least possible shearing the greater diameter of an ellipse is inclined 45° to the vertical, or 45° is the smallest or limiting

[1] The position of the major axis of a flattened ellipse with reference to the position of a vertical line rotated a definite amount, and vice versa, resulting from shearing, may be calculated from the following relation: The tangent of twice the angle between a horizontal line and a rotated vertical line (complements of the angles of column 1) is equal to twice the tangent of the angle between a horizontal line and the corresponding major diameter of the flattened ellipse (angles of column 3). Assigning any possible value to either angle, the other is easily calculable.

angle. That is to say, the highest possible dip which a cleavage can have as a result of simple shearing is 45°. The greater differences between the positions of the rotated vertical lines and the major axes of the flattened ellipses result from the smaller rotations and the largest or limiting value is 45°. The differences between the positions of the rotated verticals and the corresponding major axes of the flattened ellipses rapidly diminish in amount with the increased rotation of the verticals, and for rotations of 75° and above the differences are less than 1°. The last column (7) shows the relative efficiency in the production of cleavage of simple shearing, as compared with shortening in a single direction with consequent elongation in another direction. From this column it is seen that shearing which rotates the vertical by 10° is equivalent to a shortening of somewhat less than one-tenth; that a rotation of the vertical of 20° is equivalent to a shortening of about one-sixth; that a rotation of the vertical of 30° is equivalent to a shortening of about one-fourth; that a rotation of the vertical of 45° is equivalent to a shortening of a little more than one-third; that a rotation of 60° is equivalent to a shortening of a little more than one-half; and that a rotation of 75° is equivalent to a shortening of about three-fourths. Of course the ratios between the minor and major axes of the ellipses are the same for shortening and corresponding shearing.

In the actual production of cleavage, shortening and rotation are combined in various proportions. It would be interesting to know certainly the amount of simple shearing and of shortening which is necessary to produce ordinary slaty cleavage. I have pointed out in another place[1] that cleavage develops more largely from the formation of new minerals than from the flattening of the old mineral particles, and I am inclined to believe that a very moderate amount of shearing or shortening is sufficient to produce the structure imperfectly—possibly as little as that represented by a shortening of 10 per cent., or a rotation of the vertical of about 10°. Upon the other

[1] Loc. cit., (A), p. 635; (B), pp. 451-453.

hand it is certain that in many schists the actual shearing and shortening is several times this amount. The major axes of the flattened ellipses in the extreme phases of deformation are sometimes from 10 to 20 times as long as the minor axes.

Relations of cleavage and fissility to faults. — It has been explained that the shearing resulting in cleavage or the shearing resulting in fissility may accomplish the same kind of deformation as does thrust faulting.[1] It is equally true that if, after a fissility is produced, the rocks are under conditions of tension, numerous minor slips along planes of fissility may result, the effect of which is equivalent to normal faulting. In different districts, in the Appalachians, for instance, at various places in the Cranberry sheet, at Blowing Rock, N. C., and in Georgia and Alabama, there have been observed during the past season the results of widespread, somewhat uniformly-spaced, differential movements between laminæ at intervals varying from $\frac{1}{32}$ to $\frac{1}{4}$ of an inch. In numerous cases, as a result of these differential movements, the formations of district are brought into the same abnormal positions as would be produced by ordinary normal or thrust movement. The many slight differential movements equivalent to thrust faults, so far as my obervations have gone, are more frequent than the many slight differential movements equivalent to normal faults. In the Cranberry area a granite-gneiss, normally belonging below the Linville series, is brought forward on the north and south sides of the area by innumerable minute movements between the laminæ, to a position above the Linville series. The same sort of irregular distribution due to minute differential movements is seen in the formations of the Linville series itself. In these cases one cannot find a certain plane, or even a narrow zone, and say that here a fault has occurred. However, it is certain that in a zone of considerable width a differential movement has occurred as great as could be accomplished by a great normal or great thrust fault. For this particular form of deformation spread over a considerable area, which does not have the clear cut character of an ordinary fault,

[1] Loc. cit., (A), pp. 659–660; (B), pp. 597–598.

and yet accomplishes the same mass deformation, the term *distributive fault* is proposed. There may be distributive normal or tension faults and distributive thrust or compressive faults.

Relations of joints to bedding.—Joints have been classified into tension joints and compression joints.[1] Tension joints ordinarily form nearly normal to bedding. This results from the fact that the layers act as transmitters of forces, and that at any given place one of the principal directions of stress is ordinarily nearly normal to the layer, and the other two principal directions of stress lie in the plane of the layer. That this tendency to thus decompose the forces exists cannot be doubted. That it would be the controlling tendency in the majority of cases could not be asserted from analysis alone. However, examinations of various regions during the past season has shown me that this is often a controlling tendency, and that tension joints ordinarily do form nearly at right angles to the bedding. It has already been explained that in regions of simple folding there is one set of tensile joints,[2] and that in regions of complex folding there are two sets of tension joints. The reverse statement may be made,—that is, that where there are two sets of intersecting tension joints at right angles to each other normal to bedding, these are evidence that the region is one of complex deformation.

Compressive joints, in contrast with tensile joints, because formed in shearing planes, are ordinarily inclined to the bedding.[3] This also results from the fact that one of the principal directions of stress is usually nearly normal to bedding. Supposing the maximum stress to be in the direction of the arrows of Fig. 4, the mean stress at right angles to the plane of the figure, and least stress in the plane of the figure and at right angles to the maximum stress, in other words normal to the bedding, the position of the joints will be as shown, their planes being normal to the figure in which they are represented in section. This results from the fact that the direction of least stress

[1] Loc. cit., (A), pp. 668-671; (B), pp. 609-613.

[2] Loc. cit., (A), p. 669; (B), pp. 609-610,.

[3] Loc. cit., (A), p. 671; (B), p. 613.

is that of relief, and after rupture the differential slipping between joints will cause shortening in the direction of maximum stress and elongation in the direction of minimum stress.

When it is remembered that all the forces at work at any place may be decomposed into three principal directions of stress

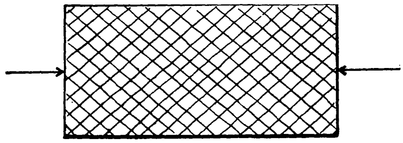

FIG. 4. Cross-section of a bed showing joints.

at right angles to one another, it would seem to follow that there would ordinarily be produced only two sets of compressive joints at the same time. To suppose that more than two sets are simultaneously produced would require that the ultimate strength was exceeded at the same moment in two of the principal directions of stress, and this is probably not a common case. One would expect, if the forces in two of the principal directions of stress are equal or nearly so, that the ruptures would be conchoidal, and this may be the explanation of some of the cone-in-cone structures. Supposing the compressive stresses to be unequal, the ruptures are produced by the maximum stress, and any one of three strains may result: (1) shortening in one direction, (2) simple shearing, and (3) shortening in one direction combined with shearing. In the first case, that of shortening in one direction and consequent elongation in a single direction, there are produced two sets of joints, but not exactly at right angles to each other. The maximum force probably bisects the acute angles (Fig. 4).[1] Subsequently, however, by differential movement between the fractured parts, it is possible that the joints may be so rotated as to change the originally acute angles to obtuse angles. The two sets of joints would only be at right angles in case the rotation stops at a definite stage. In the second case, that of simple shearing, there is one set of compressive joints

[1] Loc. cit., (A), pp. 643, 873; (B), p. 465.

and one set of tensile joints. The compressive joints lie near the longer diagonal of the deformed rectangle, and the tensile joints are near the shorter diagonal (Fig. 5). Ordinarily the former are closer together than the latter. In the third case (1) and (2) are combined; whether there are two sets of compression

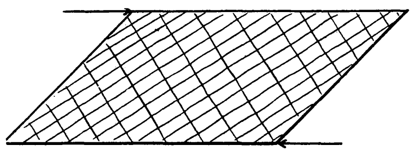

FIG. 5. Cross-section of a bed showing joints.

joints, or one is a compression and the other a tension set, will depend upon the relative amounts of shortening and shearing.

After rupture occurs as the result of tensile or compressive forces, producing one or two sets of joints, if the force in the plane of bedding at right angles to the first direction of force accumulates so as to exceed the ultimate strength of the rock, it may produce other sets of joints. In case this force is tensile, one set of joints will be produced in the normal planes. If it is compressive, any of the three cases of compressive joints above given may occur. Thus there may be produced three or four sets of intersecting joints.

From the foregoing, the criteria by which tensile and compressive joints may be separated are easily inferred. Tensile joints are ordinarily nearly normal to bedding. Compressive joints are ordinarily much inclined to bedding. Between the walls of tensile joints there is ordinarily a small space; the walls of compressive joints are, or were originally, pressed closely together. The walls of tensile joints are not likely to show differential movements nor slickensided surfaces; the walls of compressive joints generally show slight differential movements and more or less slickensided surfaces.

Relations of joints to folds.— Many cases of apparent bending of the strata are really not due to bending but to jointing. It has been pointed out that the first is a phenomenon of the zone of flow

age, and the second is a phenomenon of the zone of fracture. The special point to which I wish here to call attention is that as a result of the displacements of jointing, the strata may appear in generalized curves of anticlinal and synclinal character (Fig. 6). In various districts rocks which have not been so

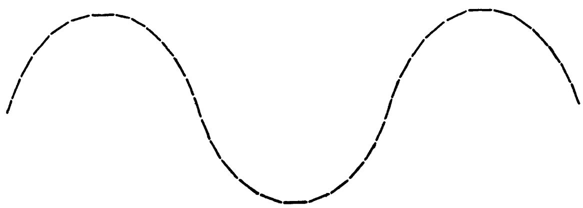

FIG. 6.

deeply buried as to be in the zone of flowage appear to be in anticlines and synclines. In these cases it is believed that the phenomena are explained as above suggested. This principle is illustrated by the slightly undulating rocks of the upper Mississippi valley. Cutting these everywhere, and in many districts in two directions at right angles to each other, are systems of joints. These joints are phenomena of fracture, and the slight bowing, which one might represent as a fold, really is not a fold in the sense of the deformation of the strata by flowage, but is bowing as a result of very slight but abrupt changes in direction at the numerous joints, the general effect being to produce a folded appearance.

The apparent bowing due largely to jointing, so well illustrated in the Mississippi valley, is still more finely illustrated by the Allegheny Mountains. The limestones and sandstones of this mountain system, ordinarily regarded as deformed mainly by folding, are largely deformed by jointing. If the course of the strata be roughly platted, they will appear to be in continuous undulating curves. However, the rocks are everywhere cut by two intersecting sets of joints at right angles to each other, and it appears to be the case that the curved deformation is really not mainly that of folding, but mainly that of fracture

(Fig. 6). However, I would not assert that to some extent the material had not also flowed at various times before the stresses exceeded the ultimate strength of the rocks and ruptures occurred. Even if the apparent gentle curves of the strata can be more accurately represented diagrammatically by placing end to end a large number of broken lines with slight changes of direction, the curves indicated by the lines would have the forms of folds given under Analysis of Folds.[1] In the weaker shaly layers between sandstones and limestones the deformation is in many cases largely that of shearing, this being due to the differential movement between the two bounding strong layers. In the weaker layers the jointing is therefore in two diagonal sets.

In the case of the Mississippi valley it is clear that the stresses producing the jointing are locally still at work. For instance, at the combined rocks at Appleton,[2] a recent rupture occurred which was sufficient to make considerable displacements in the artificial works. Other cases of a similar kind have been given by Reade.[3] The foregoing cases show that the apparently horizontal rocks of the Palæozoic at the present time, are locally under such stress that when a slight amount of material is removed, and thus the beds not held so firmly in their position, the ultimate strength is exceeded and rupture occurs. Denudation is ever lightening the load of the strata, and from time to time, as a result of this, the abrupt deformations of jointing or faulting may occur. Before the time of rupture, it may be that the stresses, while not sufficient to produce rupture, may still surpass the elastic limit and result in slow flowage.

C. R. VAN HISE.

[1] Loc. cit., (A), pp. 603–633; (B), pp. 312–353.

[2] On a recent Rock Flexure, by FRANK CRAMER. Am. Jour. Sci., Vol. XXXIX, 1890, pp. 220–225.

[3] On the Cause of active compressive Stress in Rocks and recent Rock Flexures, by T. MELLARDE READE. Am. Jour. Sci., Vol. XLI, 1891, pp 409–414.